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AN EPISODIC MEMORY FOR A SIMULATED AUTONOMOUS ROBOT

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Abstract: In this paper we present the development of an episodic memory module for the cognitive architecture controlling an autonomous mobile simulated robot, in a simulated 3D environment. The episodic memory has the role of improving the navigation system of the robot, by evoking the objects to be considered in planning, according to episodic remembrance of earlier contacts with those objects in the past. We introduce the main background on human memory systems and episodic memory study, and provide the main ideas behind our experiment.

Keywords: episodic memory, autonomous mobile robot, navigation

1. INTRODUCTION

The research on autonomous mobile robots [1–3] has being very intense in the recent literature. Tasks like e.g. navigation and planning [4] have attracted the attention of many researchers in the field. Research in autonomous mobile robotics is usually split into two main sub-fields. The first, which we will be calling here *hard* robotics, leads with real robots, and is concerned mainly in dealing with real world problems, like e.g. noise interference, sensors and actuators and real world robotics tasks. The other subfield leads with simulated robots in simulated environments, and is more concerned with strategies, general algorithms, complexity issues and new techniques applied to the robotics domain. This second sub-field, which we will be calling here *soft* robotics is more multi-disciplinary, sometimes running into other fields of research, like e.g. artificial life and cognitive science. In both the hard robotics and soft robotics subdomains, an approach, which is being called as cognitive robotics [5, 6] tries to associate cognition to robot control. In some cases, this inspiration in cognition is more biological [7]. In other cases, this inspiration is really towards the construction of humanoid robots [8]. Sometimes, the robotics issue is abstracted, and the robot is treated simply like an agent [9]. A general field, *Cognitive Systems* [10] was created to deal exclusively with these ideas.

An important concept related to cognitive systems research is the concept of a Cognitive Architecture [11, 12]. A cognitive architecture is usually a control system for a robot, which comprises a set of modules responsible for the implementation of cognitive capabilities in such control system. Cognitive architectures are mainly inspired by human neurocognitive and psychological abilities, where typical human cognitive tasks as perception, learning, memory, emotions, reasoning, decision-making, behavior, language, consciousness, etc. are in some way modeled and used as a source of inspiration in order to enhance the capabilities of autonomous mobile robots. In many situations, robots equiped with a cognitive architecture are called artificial creatures [13]. Many of such cognitive abilities were successfully reported as very useful in making smarter creatures. Among others, abilities as emotions, learning, language evolution, action selection and either consciousness brought the performance of such creatures to an amazing level.

Nevertheless, there seems to be at least one of such cognitive abilities which was not so widely explored since so far. This ability is what we may refer from now on as *episodic memory* [14]. The first creatures used to live only in the present, sensoring its surroundings and choosing its action based only on the current situation. Next generations of creatures enhanced that by living not only on the present, but also with an eye on the future, being able to making plans and creating expectations, which clearly sophisticated its behavior. But few of them were able to refer to its past, just like we do as humans.

We (humans) are able to remember what we did by this morning, some issues we lived last week, 2 months ago or even years ago. And more than this, we are able to build up a chronological time line, and order such events and locate them in this time line. We use this memory in order to learn things and to help us in performing our daily behavior. This is currently a missing gap in cognitive systems research. It will be an important improvement if our creatures were able to remember that they already were in such and such location, where they met such and such objects and creatures, and where such and such episodes were testified by them.

This is the main motivation of this work. Even though some related initiatives already started to appear in the literature [12, 15–22], we are still very far from having this as a well known technology to be widely used in intelligent agents. In this work we report on our ongoing efforts to bring up such technology by building up a cognitive architecture where episodic memory is a central capability.

2. HUMAN MEMORY SYSTEM AND EPISODIC MEMORY

The term "memory" can be used in many different contexts, addressing different kinds of things. It can be used, e.g. in the context of dynamical systems, to designate a specific state variable, which maintains its value through time, and is able to make an influence on the overall system state. We can also use the term "memory" in the context of a computer architecture, and so a memory will be an addressable array of flip-flop circuits, carrying on some value, during many cycles of machine clock. But the term "memory" can also be used in the context of human memory. Human memory, opposite to a dynamical system or a computer memory, is a very sophisticated system, with many different behaviors, which comprise, in a deeper analysis, an inter-related complex of different kinds of memory systems. We will see, next, that episodic memory is a specific subsystem which is a part of the whole human memory system.

2.1. Human Memory System

The human memory system has received a special attention from the scientific community in general, therefore several research areas have focused their efforts in better understanding this complex system. Although the research on memory, in different areas, vary in aims and perspectives, they usually consider the memory system divided in the following basic aspects [23]:

- Working Memory
- Short Term Memory
- Long Term Memory
  - Non-declarative Memory
    - Perceptual Memory
    - Procedural Memory
  - Declarative Memory
    - Semantic Memory
    - Episodic Memory

In a first glance, the human memory system is divided between Working Memory, Short Term Memory and Long Term Memory.

The *Working Memory* is used to store transient information during perception, reasoning, planning or other cognitive functions. Its capacity in time and space is very short, ranging from a few dozen itens, and periods ranging from a few seconds up to a few minutes.

The *Short Term Memory* is an intermediary kind of transient repository, which accomodates conscious information (information which reached consciousness) in a buffer ranging from 3 to 6 hours, during a process of consolidation when this information is permanently stored in long term memory.

Finally, the *Long Term Memory* is a very complex memory subsystem, where different kinds of information are stored for long term retrieval. It can be decomposed into many different subsystems. The division described here, though, is not a consensus among memory experts. Some experts may say that the same kind of subdivisions employed here for long term memory, may apply also to short term memory and working memory. Following [23], we will be dividing long term memory into non-declarative and declarative memory.

Declarative Memories are memories that refers to *facts* that can be explicitly declared, like e.g. a proposition given by a phrase in a particular language. *Non-declarative memories*, on the other side, constitute the many different parts involved in a declarative memory, like e.g., the many different words used in a phrase. In this sense, non-declarative memories are used to record perceptions and actions, given rise to a further sub-division of non-declarative memories into Perceptual and Procedural memories.

The *Perceptual Memory* is the memory of categories of things which can be perceived by a Perceptual System. It includes different things attributes and patterns which can be categorized by a perceptual system. Each instance of a perceptual memory is a representation of a category used during perception.

The *Procedural Memory* is the memory of actions and behaviors of a system. It is a non-declarative memory which refers to a "how to" kind of information, usually consisting of a record of possible motor and behavioral skills.

Declarative memories, on the other side, are used to describe *knowledge*, as it appears in complete sentences in a natural language. They can be used to store both atemporal, general common-sense knowledge, like e.g. "Dogs are a specific kind of animal", or "My name is Paul", or used to store specific temporal event knowledge, like e.g. "Yesterday, from 23:00 to midnight I was sleeping in my bed". So, declarative memory can be divided into two different subsystems: Semantic Memory and Episodic Memory.

The *Semantic Memory* is used to record facts of a general kind, not contextualized in time and space. The *Episodic Memory*, on the other hand, is used to store facts particularly contextualized in time and space, forming "episodes" which refers to information specific to a particular location and timeframe.

Cognitive studies with humans which had some kind of impairment on their memory system, due to brain damage, show that it is possible to have damage in some kinds of memories while still retaining other kinds of memories. In cognitive systems research, we can also address the same observation. There may be cognitive systems which are responsible for providing memory capabilities of one kind, while not providing memory capabilities of other kinds.

In this work, we are particularly interested in the Episodic Memory, so we will focus our attention and detain ourselves to more deeply explore its inherent cognitive capabilities.

3. The Episodic Memory

Episodic Memory is a neurocognitive mechanism for accessing timing contextualized information that naturally makes part of the human process of decision making, usually

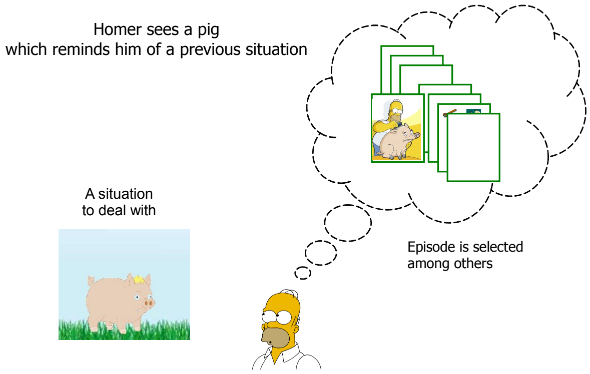

Figure 1: Episodic Memory

enhancing the chances of a successful behavior. This assertion is supported by human psychological research which indicate that the knowledge of his/her personal history enhances one's person ability to accomplish several cognitive capabilities in the context of sensing, reasoning and learning.

Take as an example what is happening in figure 1. The character in the figure is dealing with a particular situation, and needs to decide what to do. Using objects which are perceived in the current situation as a hint, the episodic memory system is triggered, and a past situation where this object appeared is recovered as an episode. The character is now able to use this information in order to decide what to do in the current situation.

As in the case of the character in figure 1, in an artificial system, we would like to include an episodic memory subsystem, whose purpose is to assist the process of learning and ultimately providing a mechanism for better performance of intelligent autonomous agents in dynamic and possibly complex environments.

The main unit of information in an Episodic Memory system is called an *episode*. An episode is a record defined within a period of time and formed from information regarding the agent's task or other specific data observed in the environment. It also contains a measurement of "how successful" or relevant that information was for accomplishing a task in a past situation. In other words, the episode links particular data to a particular time and place in the environment and provides an indication of how to use that information to successfully perform a task. Therefore, along the time, it builds a repository of previous gathered experiences. Then whenever the creature faces certain situations and has to decide how to proceed next, it makes use of its repository of episodes to evaluate the best decision to make.

Episodes may be *State-based Episodes* or *Scene-based Episodes*. State-based episodes store the episode as sequences of an agent's states (including environmental sensed states). State-based episodes are easier to store, but more difficult to be used by higher-level cognitive functions. In artificial cognitive systems they are the most popular option for implementation, due to the easiness of its implementation, but they can be used only on specific kinds of applications, as its use on more sophisticated applications will be difficulted.

Scene-based Episodes encode a time-space segment as a scene. In this scene, there are objects which were consciously perceived by the agent, and an action, performed by the agent itself or other agents appearing in the scene. Scene-based Episodes, can be viewed as interpreted versions of state-based episodes. They are easier to be used by high-level cognitive functions, as they already segment the scene into discrete elements, which are playing its own role in the scene dynamics. At the same time, they are more difficult to be implemented in artificial systems, because they require a process of interpretation of sensorial information in order to discover the objects and actions being performed in the environment.

Episodes can also be *autobiographic* and *non-autobiographic*. Autobiographic episodes are those episodes where the agent itself is performing the action being described in the episode. On the contrary, on non-autobiographic episodes, the subject of the action is another agent. In this case, these actions are being observed by the current agent and memorized as something seen, but not done by the agent itself.

An episodic memory system do require three major subsystems [16]:

- Encoding Subsystem
- Storage Subsystem
- Retrieval Subsystem

The *Encoding* subsystem is responsible for capturing the episode from the perception system (and maybe the behavior system, in the case of autobiographical episodes), and setting up the way the episodes are captured and stored. This subsystem addresses issues concerning the proper time to record the episodes and what information is to be stored within the episodes.

The *Storage* subsystem is responsible for getting the episode from the encoding subsystem and recording it in a permanent storage. This subsystem is responsible to define how the episodes are maintained, addressing issues such as memory decay and possibly merging of episodes to compact storage.

The *Retrieval* subsystem is responsible for providing episodes for being used by other cognitive functions. In other words, it defines how memory retrieval is triggered. This subsystem addresses issues related to the cue determination (which key data is used to trigger an episode) and how to use the retrieved episode.

Finally, to summarize this brief accounting of episodic memory, it is important to point out some possible uses of episodic memory in a cognitive architecture. The main use of episodic memory is to implement a cognitive capability called “mental time travel”. Mental time travel is the capacity of “going back in time and space” and retrieving episodes related to a present situation. This capacity can be used to improve and enhance other cognitive capabilities, like e.g. perception, learning, planning, decision-making and action selection and execution.

For example, in *perception*, episodes may help in the process of detecting repetition and relevant input. Besides that, the mechanism provides the retrieval of features outside current perception which are relevant to the current task. Episodic memory also assists the mechanisms of action modeling and environment modeling.

In *learning*, episodic memory aids the learning processes providing an efficient mechanism of reviewing experiences and learning from them. Comparing multiple events simultaneously, the learning system is able to generalize knowledge. In addition, provides a way of recording previous failures and successes, which can be useful later for planning and decision-making.

It also aids in *planning* and *decision making* processes through predicting the outcome of possible courses of actions. Basically, the episodic memory allows the person/agent to review its own past action or of another one. Decisions which were useful in the past may be employed to solve current situations. Decisions which did not succeed may be avoided.

In *action selection and execution*, episodic memory may be used to keep track of progress and manage long-term goals. Using episodic memory, the system may be able to know that specific parts of a plan have already been executed, so the action-selection algorithm may define the next steps of a plan to be executed.

Besides that, episodic memory allows the person/agent to develop a sense of identity, as the episodes creates what could be accounted as the personal history of an individual. This personal history encompass information of events which were consciously perceived and performed by the person (or agent).

4. Episodic Memory in Cognitive Systems Research

Most of the research concerning Episodic Memory within Computer systems was published in the last five years. Though being still an incipient area of research, the computational study of Episodic Memory has provided interesting insights and these first works exploring its capabilities have presented very stimulating and promising results. The following research have been the main references for our work.

- Nuxoll and Laird’s Episodic Memory for Soar
- Dodd’s Episodic Memory for ISAC (Intelligent Soft Arm Control)
- Brom’s virtual RPG actor with Episodic Memory
- Kim’s virtual creature Rity’s and its Episodic Memory
- Ho’s Autobiographic Memory Control Architecture
- Tecuci’s Generic Episodic Memory Module

Soar (originally known as SOAR: State Operator And Result) is a general purpose cognitive architecture being developed since a long time by the team of Prof. John Laird at University of Michigan, which was recently enhanced with an Episodic memory module [16], developed by Andrew Nuxoll. They performed several different experiments where different approaches for episode were tested and results extensively analyzed. For instance, they have analyzed effectiveness of partial versus complete matching algorithms during the retrieval phase, providing insights and alerting to trade-offs to be considered when dealing with cue and feature selection. The work presented very promising results and concepts were explored within a computer game environment.

The team of Prof. Kazuhiko Kawamura from the Cognitive Robotics Lab at Vanderbilt University developed ISAC (Intelligent Soft Arm Control), a cognitive robotic system - more specifically - a humanoid robot equipped with airpowered actuators designed to work safely with humans and used as a research platform for human-humanoid robotic interaction and robotic embodied cognitive systems. Will Dodd, a member of Prof. Kawamura team presented interesting results [15] when enhanced the ISAC with an Episodic Memory module. They have analyzed the impact of the use of Episodic Memory in terms of the robot performance and computational resources.

Prof. Cyril Brom, from Charles University in Prague, Czech Republic, developed a project to enhance an RPG (i.e. a role-playing game) actor, a non-player character, with a Memory module that allows it to reconstruct its personal story [17]. Although the focus of the project is regarded with linguistics, it explores and analyzes the basis of an Episodic Memory architecture, where episode structure, feature relevance and computational resources demanded are special issues to consider and which are crucial to the architecture efficiency. They show that in their game scenario, actors with Episodic Memory present a better performance than those without it, but only in low dynamic worlds and that the memory consumption is acceptable.

Prof. Jong-Hwan Kim and his team from the Korea Advanced Institute of Science and Technology (KAIST), developed Rity, a dog-like virtual creature that is the “software robot” unit of the *Ubibot*: the ubiquitous robot system project at KAIST, which has largely evolved during the last ten years. The Episodic Memory architecture was mainly developed by researchers N. S. Kuppuswami and Se-Hyoung Cho, from Kim’s team, in the middle of the decade in order to provide a cognitive task selection mechanism for Rity. The creature's architecture explores the advantages of a reactive architecture with the higher level planning offered by the Episodic Memory, in addition to provide a learning mechanism that evolves with time, since Rity's decision making process is more efficient as the creature's experience grows [19].

In the Adaptive Systems Research Group at the University of Hertfordshire, UK, coordinated by Profs. Kerstin Dautenhahn and Chrystopher Nehaniv, the researcher Wan Ching Ho developed an autobiographic memory control architecture (a kind of Episodic Memory) for virtual creatures [22]. The architecture is mainly focused on navigation problems, but its results are very promising confirming the effectiveness of the use of Episodic Memory in decision-making problems. In the architecture, whenever certain internal states of the creature are lower than a threshold, the creature searches through all the records in memory and reconstructs an event using a "meaningful search key" to recognize the possible sequence of how an event should be organized (event reconstruction mechanism). The records that match the key then provide the target resources to satisfy the current internal needs.

Dan Tecuci, from the University of Texas, designed a generic Episodic Memory module that can be attached to a variety of applications. He proposes that each generic episode presents thee dimensions that will be used during the retrieval phase and according to the type of application: *context*: general setting in which an episode occurs, for example, it could be the initial state and the goal of the episode, *contents*: ordered set of events that make up the episode and *outcome*: the evaluation of the episode's effect. The kind of task (planning oriented, goal recognition or classification) to be executed defines a scope focusing its procedures on one dimension of the episodes. For example, a classification-like task mainly recognizes whether a goal is solvable according to a state of the world. This corresponds to retrieval based on *episode context* and using the *outcome* of the retrieved episodes (i.e. their success) for classification. The generic module provides an API with two basic functions: store and retrieve. *Store* takes a new Episode represented as a triple [context, contents, outcome] and stores it in memory, indexing it along the three dimensions and *retrieve* takes a cue (i.e. a partially specified Episode) and a dimension and retrieves the most similar prior episodes along that dimension [20, 21]. This work provides interesting insights in how to efficiently establish the features that an episode must present in order to be actually useful after being retrieved and interpreted and those features that a *cue* must address to allow the retrieval of the most promising episodes

5. The CACE Project - Cognitive Artificial Creatures Environment

5.1. General characteristics and motivation

The CACE project - Cognitive Artificial Creatures Environment, being developed by our group at the University of Campinas, Brazil, consists of a virtual environment where robots (virtual creatures), controlled by a cognitive architecture, try to accomplish a given task. The task is a "leaflet" containing a sequence of specific objects that must be collected in the environment and delivered in a specific place. The performance is basically measured in how fast the robots correctly accomplish their tasks along the available time. Figure 2 presents a screen shot of the scenario of the environment.

The environment is essentially dynamic, since the robots can change the position of the objects by hiding them under the ground or simply moving them to other positions in the environment space. Figures 3 and 4 show the robots and other entities of the scenario: food (nuts and apples), obstacles (in pink) and objects (bricks with different colors).

In our current experiments, competition among the robots is encouraged and they never help each other or form teams. Consequently, simply moving an object that does not belong to its private *leaflet*, but that may belong to others, may be an interesting move to interfere in the other robots' performance. In addition, homeostatic internal states must be observed: the robots spend energy along the time, which has to be reestablished by food consuming. However, the food may be perishable or not. Consequently, along the time, it is expected that the robots develop a strategy where perishable food is consumed preferably and within their validity period and the best place to store the non-perishable food for future consumption and precaution.

In this work, our main purpose is the development of an "episodic memory" module for CACE, mainly consisted in storing and using the agents' previous actions and other spe-

Figure 2: Screenshot of the Environment

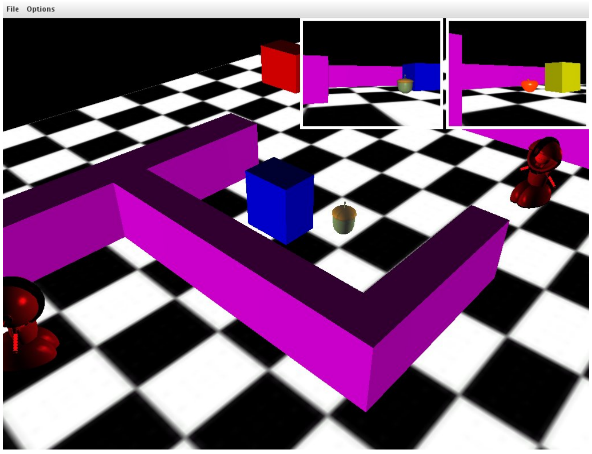

Figure 3: Robot avoiding obstacles and moving

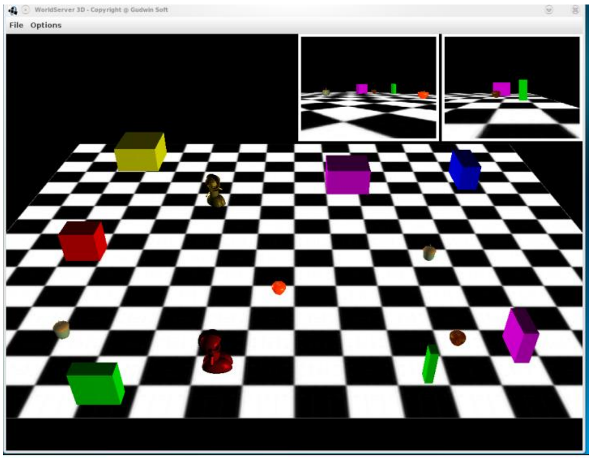

Figure 4: Two robots looking for colored objects and food towards a non-perishable food (nut)

cific data, while exploring the simulation environment. This module could be interpreted as a metaphor of a simplified "declarative memory" of each agent. The agent could access this information whenever a similar situation emerges and then decide how to proceed. Ultimately, the project aims in verifying if the use of the "episodic memories" actually enhances the agents' performance in accomplishing their tasks.

5.2. The Use of Episodic Memory

In our work, the Episodic Memory is mainly used in decision planning. More specifically, it must aid in handling and analyzing three issues that are described in the following sections.

Path planning

When the environment is large, it is not feasible to plan using all known obstacles and objects. So, the information within the episodes is used to evaluate feasible paths (e.g. without obstacles) during the navigation mechanism. Figure 5 illus-

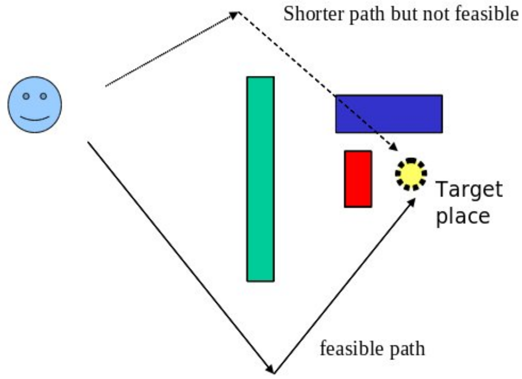

Figure 5: Use of Episodic Memory in path-planning

trates the idea. In other words, the information within the episodes are used during the generation of a path plan and, consequently, may also anticipate problems while the creature is navigating. Since the environment is dynamic, there is no certainty regarding the path, but the episode provides certain level of probability once refers to a path previously observed.

After the path planning module evaluate all candidate paths, the *way points* that form each path are analyzed based on the information present in the Episodic Memory. If there is no obstacle along the path it is considered feasible and the shortest path among those evaluated as feasible is chosen.

Episodes instead of world map

Information regarding obstacles, food and other creatures perceived by the visual system are recorded within an episode. Instead of storing this information in a "world map", they are maintained in episodes within the Episodic Memory. During planning process, episodes are recollected in the Working Memory, and only "remembered" things are considered during the decision making process. This "remembered" information comes from episodes that matched the current situation in a certain level of similarity. A partial matching algorithm using different approaches have been considered when comparing the cue of the current situation with the episode in Memory: number of same features, key features in common and relevance of features in common.

Possibility of emergence of strategies

The creature's behavior is not deterministic. The creature's action decision mechanism is accomplished based on a behavior network [24–27] that provides a certain level of flexibility to the planning mechanism. It is possible thanks to inherent characteristics of behavior networks. Therefore, while following a plan towards a "short-term" goal, opportunistic decisions may be taken that satisfies "long-term" goals.

In order to explore this behavior network characteristic, we intend to analyze if certain strategies may emerge during the simulations. One example is based on what we define in our work as "non-autobiographical episodes": those in which the creature is a mere observer and not the subject of the action.

For example, observing the opponents behaviors (perceiving episodes where the opponent is the agent performing actions) a creature may infer the opponents' goals. Then, an agent may try to hide the objects that the opponents need in order to decrease their performance.

6. Conclusion

Despite being still a young research area, in the context of computational systems, the study of Episodic Memory in cognitive systems has provided very interesting insights. The works that have explored its computational capabilities have presented very promising results which have consequently increased the scientific community curiosity. On the other hand, exactly for being such an incipient area, there is still too much to be explored, analyzed and experienced. Recent research have shown that trade-offs must be taken into account and not all scenarios may get much benefit from the use of Episodic Memory. However, as cognitive systems become more and more complex and have to handle more and more information, mechanisms with certain cognitive capabilities, such as Episodic Memory, will be a prerogative.

The current work is still in progress and the final results and analysis will be published in future papers.

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